Biogeochemical and nutrient removal patterns of created riparian wetlands: Sixth-year results

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Introduction

As part of a long-term, large-scale experiment on self-design, two wetland basins at The Olentangy River Wetland Research Park were set up as a planting experiment, i.e., one basin was planted in 1994 with 2400 individuals of macrophytes representing 12 species while a second wetland basin remained unplanted (Mitsch et al., 1998). In the 6 years of wetland development since that planting, the basins have gone through 6 growing seasons that have been characterized as follows:

• Year 1 (1994) - Wetland 1 was planted in May with Wetland 2 as unplanted control. Essentially both basins were algal ponds with few macrophytes.

• Year 2 (1995) - Wetland 1 plants developed, particularly around the perimeter to about 13% macrophyte cover in August, compared to essentially no macrophyte cover in Wetland 2. Floods in late June and early August brought in large carp with waters remaining turbid through much of the rest of the year.

• Year 3 (1996) - Wetland 1 continued to develop in vegetation cover with about 39% cover. Unplanted Wetland 2, particularly after spring drawdown in both wetlands to install sedimentation markers, developed to about 35% macrophyte cover by August, essentially catching up with the planted wetland within 3 growing seasons.

• Year 4 (1997) - Macrophyte growth continued to increase in both wetlands with about 54% cover in Wetland 1 and 58% cover in Wetland 2.

• Year 5 (1998) - Macrophyte cover is similar in the two basins but Wetland 2 is beginning to be dominated by highly productive *Typha* spp. while Wetland 1 still has a wider diversity of cover and is not dominated by *Typha* spp. In other words, Wetland 1 plant cover is now more diverse.

• Year 6 (1999) - Wetland 2 is dominated by *Typha* while Wetland 1 continues to be dominated by 3-4 of the planted species.

This study reports water quality results for the sixth year (1999). Other studies of the water quality of these wetlands are reported for Year 1 (Mitsch et al., 1995); Year 2 (Wehr and Mitsch, 1996; Mitsch and Nairn, 1996; Nairn and Mitsch, 1997); Year 3 (Mortensen et al., 1997; Mitsch and Carmichael, 1997; Nairn and Mitsch, 1997; Vorwerk and Mitsch, 1998); Year 4 (Mitsch and Montgomery, 1998; Spieles and Mitsch, 1998); and Year 5 (Mitsch et al., 1999). Two undergraduate honors theses (Wehr, 1995; Vorwerk,

Table 1. Water quality sampling at Olentangy River Wetland site in 1999.

Sample frequency	# sampling stations	Period in 1999	Equipment	Parameters measured
30 minute	4 (two middles; two near outflows)	Jan - Dec	YSI 6000UPG sondes	temperature dissolved oxygen pH redox conductivity turbidity
twice daily	3 (inflow-W1; two outflows)	Jan-Dec	YSI probe	temperature dissolved oxygen pH redox conductivity
			Hach turbidimeter(Lab)	turbidity
weekly	7 (river; 1 inflow-W1; 2 middles; 2 outflows; swale)	Jan-Dec	YSI probe	temperature dissolved oxygen pH conductivity
			Hach turbidimeter(Lab)	turbidity
			LACHAT QuikChem IV(Lab)	total phosphorus soluble reactive P $NO_3 + NO_2$

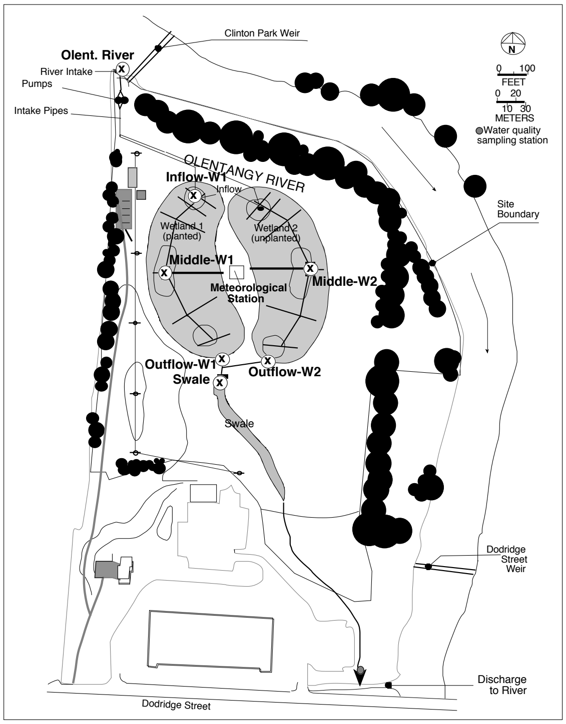

Figure 1. Location of water sampling stations used in 1999 for the experimental wetlands.

1997), one Master's thesis (Harter, 1999), two Master's theses from Europe (Mortensen and Lanzky, 1996; Kang, 1999) and three dissertations (Nairn, 1996; Spieles, 1998; Liptak, 2000) have also investigated aspects of water quality at the site. Four journal articles (Mitsch et al., 1998; Kang et al., 1998; Nairn and Mitsch, 2000; Spieles and Mitsch, 2000) have been published on water quality changes through these experimental wetlands.

Methods

A summary of the water quality monitoring protocol for the two experimental wetlands in 1999 is shown in Table 1. Locations of the various sampling stations are shown in Figure 1.

Weekly sampling

Weekly water sampling, instituted in late April 1994 continued through 1999. Samples were taken at 7 stations in 1999 as in 1998 and 1997. One 1000 ml sample was collected at each of the 7 sites. Water samples were taken to the Ecosystem Analytical Laboratory at Ohio State where subsamples were filtered and frozen for later measurement of soluble reactive phosphorus. Unfiltered samples were preserved with concentrated H_2SO_4 (2 ml/liter sample) and frozen for later analysis of total phosphorus and nitrate+nitrite (NO_3+NO_2). A raw sample was also stored for any new or additional analyses to be added. Sample preparation and preservation was completed within 48 hours of original collection.

Daily sampling

Two-per-day water sampling, also initiated in 1994, continued through 1999 by the staff and students of the Wetlands Program at Ohio State. Inflow of Wetland 1 (assumed after several studies to represent the inflow to both basins) and the outflows of Wetland 1 and Wetland 2 were monitored in 1999 for temperature, dissolved oxygen, pH, conductivity, and redox with a YSI probe. Instruments were calibrated and checked for battery power frequently. Each Time a 100-ml Nalgene bottle was used to take a sample for latter of measurement of turbidity In the lab and at each of the three stations.

Sample analysis

For all laboratory analyses in 1999, Standard Methods for the Examination of Water and Wastewater, 17th Edition (APHA, 1989) and EPA Methods for Chemical Analysis of Water and Wastes (U.S. EPA, 1983) were followed. Total Phosphorus, Soluble Reactive Phosphorus, and Nitrate+ Nitrite were analyzed on a quarterly or more frequent basis on a Lachat QuikChem IV automated system and Lachat methods (U.S. EPA, 1983). Both total phosphorus and soluble reactive phosphorus methods employed the ascorbic acid and a molybdate color reagent method. For soluble reactive phosphorus and total phosphorus, Total phosphorus samples were first digested by adding 0.5 ml of 5.6N H_2SO_4 and 0.2 g NH_3SO_4 to 25 ml of sample and exposing the samples to a heated and pressurized environment for 30 minutes in an autoclave. Nitrate+nitrate, run on the Lachat QuikChem IV automated system, used the cadmium reduction method.

Results

Water quality results for 1999 weekly and two-per-day sampling are summarized in Table 2 while percent change through the wetlands and statistical significance are summarized in Table 3. Seasonal patterns of nutrients are shown in Figure 2. Each of the parameters is discussed separately below.

Nitrate-nitrogen

Nitrate+nitrite patterns in the inflow and outflows of the experimental wetlands for 1999 are shown in Figure 2. Concentrations ranged from 3 to 7 mg-N/L in the inflow from mid-January through mid-May and less that 2 mg-N/L for the rest of the year. As in previous years, nitrate-nitrogen reduction mostly occurs when there are lower flows through the wetlands, especially in the growing season of May through September or October.

Nitrate decreased overall in 1999 by 30% in Wetland 1 and 33% in Wetland 2. Differences between wetlands were not significant (α=0.05). Retention in 1998 was almost the same at 33 % in Wetland 1 and 39% in Wetland 2 but doubled from 1997 when only 18% was retained in Wetland

Table 2. Summary of water quality measurements at Olentangy River experimental wetlands, 1996 through 1998. Two -per-day sampling refers to dawn-dusk sampling done almost every day that water is flowing. Numbers are average ± std. error (# of samples).

Parameter	Year	Olent. River	Inflow	Middle-W1	Middle-W2	Outflow-W1	Outflow-W2	Swale
Total P, µg-P/L	1996	185±15 (40)	191±18 (30)	85±11 (33)	77±9 (34)	68±8 (34)	64±9 (35)	62±9 (33)
	1997	149±16 (46)	146±17 (45)	99±7(39)	113±13 (38)	125±20 (41)	120±12 (43)	94±7 (44)
	1998	244±28 (47)	186±16 (46)	129±15 (47)	133±14 (47)	98±10 (47)	98±11 (47)	31±7 (47)
	1999	194±35 (48)	126±11 (44)	99±11 (43)	138±22 (41)	92±17 (44)	76±12 (45)	70±9 (45)
SRP, µg-P/L	1996	58±8 (38)	70±11(29)	19±4 (33)	16±4 (33)	8±1 (33)	9±2 (33)	9±2 (32)
	1997	50±6 (48)	67±12 (47)	23±3 (40)	25±3 (39)	26±3 (37)	23±3 (40)	37±13 (39)
	1998	89±11 (47)	82±10 (46)	45±9 (47)	45±9 (47)	27±6 (47)	31±7 (47)	31±7(47)
	1999	97±10 (47)	94±10 (43)	46± 8 (45)	33±6 (44)	27±4 (47)	24±4 (46)	23±4 (48)
$NO_3 + NO_2$, mg-N/L	1996	4.60±0.41 (38)	4.42±0.42 (29)	3.08±0.38(34)	2.89±0.32(34)	2.97±0.40(34)	3.30±0.38(34)	3.19±0.47(31)
	1997	4.89±0.97 (48)	4.23±0.75 (47)	2.92±0.62 (39)	3.02±0.69 (39)	3.51±0.71 (42)	3.55±0.71 (42)	3.45±0.71 (44)
	1998	2.79±0.39 (47)	2.72±36 (46)	2.06 ±0.35 (47)	2.02 ±0.33 (47)	1.83±0.32 (47)	1.67±0.34 (47)	1.82±0.33 (45)
	1999	1.94±0.24 (47)	1.91±0.24 (44)	1.51±0.29 (42)	1.46±0.25 (44)	1.33±0.28 (45)	1.28±0.24 (45)	1.20±0.23 (47)
Turbidity, NTU [1]	1996		35±3 (319)			21±2 (404)	20±2 (407)	
	1997		28±2 (453)			26±2 (426)	27±2 (447)	
	1998		25±2 (446)			16±1 (459)	16±1 (462)	
	1999		25±2(493)			19±1 (524)	20±1 (521)	
D.O., mg/L [1]	1996		9.69±0.19 (278)			10.55±0.21(336)	10.48±0.18(338)	
	1997		9.90±0.2 (454)			11.38±0.28 (412)	11.32±0.29 (430)	
	1998		9.40±0.14 (430)			11.98±0.26 (433)	11.66±0.25 (436)	
	1999		8.70±0.15 (463)			9.12±0.24 (486)	8.59±0.21 (489)	
Temp, °C [1]	1996		14.9±0.5 (302)			15.5±0.4 (373)	15.7±0.4 (373)	
	1997		13.2 ±0.4 (476)			13.7±0.4 (443)	13.7±0.4 (464)	
	1998		14.6±0.4 (456)			15.0±0.4 (471)	15.1±0.4 (475)	
	1999		14.9±0.4 (488)			14.8±0.4 (512)	14.6±0.4 (509)	
Cond., µS/cm [1]	1996		535±6(282)			452±5(349)	454±5(350)	
	1997		621±7 (401)			576±7 (364)	593±7 (385)	
	1998		539±6 (450)			487±5 (462)	502±6 (467)	
	1999		550±8 (488)			527±8 (513)	533±8 (512)	
pH [1]	1996		7.91±0.02(300)			8.17±0.03(367)	8.19±0.03(368)	
	1997		7.94±0.03 (443)			8.24±0.04 (412)	8.20±0.04 (431)	
	1998		8.18±0.04 (365)			8.47±0.04 (374)	8.38±0.04 (375)	
	1999		7.74±0.02 (480)			7.87±0.03 (502)	7.80±0.02 (502)	
Redox, mV[1]	1996		394±4(213)			387±3(263)	384±3(265)	
	1997		433±3 (338)			433±3 (352)	430±4 (377)	
	1998		333±6 (440)			309±6 (450)	307±6 (456)	
	1999		302±7 (436)			283±7 (460)	281±7 (457)	

[1] two-per-day sampling

1 and 17% in Wetland 2. There were 33 and 25% decreases respectively for the two wetlands in 1996. Nitrate-nitrogen decreased in a very similar and almost linear pattern through the two wetlands (Figure 3).

Soluble Reactive Phosphorus

Figure 2 illustrates the concentrations of soluble reactive phosphorus (SRP) for 1999. There were few pulses in the river water this year and there was again a consistent pattern of separation of inflow and outflow concentrations, particularly in the growing season.

For the fourth year in a row, a seasonal pattern was observed with well-defined decreases in SRP from inflow to outflow during the summer months and less obvious patterns in spring and winter. On average, SRP decreased by 71 and 75% in Wetlands 1 and 2 respectively in 1999. Rates were 67% in Wetland 1 and 63% in Wetland 2 in 1998. In 1997, SRP decreased by 61% in Wetland 1 and 66% in Wetland 2. In 1996, the respective decreases were 89 and 87%.

Outflow concentrations of SRP averaged 24-27 µg-P/L in 1999, about the same as the 27-31 µg-P/L in 1998 and the 23-26 µg-P/L seen in 1997. Concentrations in 1996 in the outflow were 8-9 µg-P/L. The decreases in SRP through the wetlands was exponential (Figure 3), suggesting that most of the SRP is removed in the first half of the wetlands.

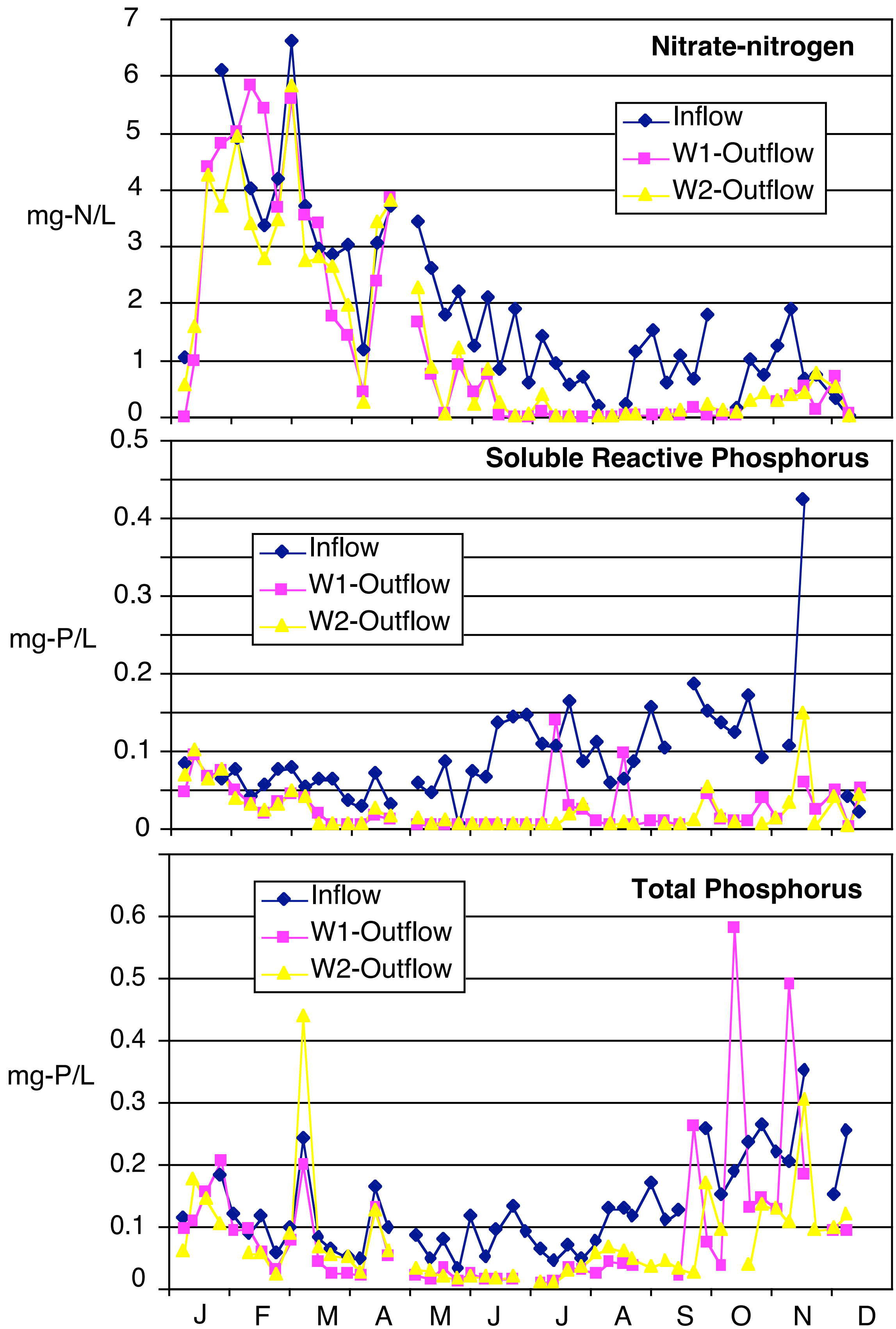

Figure 2. Nitrate-nitrogen, soluble reactive phosphorus, and total phosphorus in inflow and two wetland outflows in 1999.

Total Phosphorus

There was a noticeable pattern of higher phosphorus in the river in the non-growing season and lower concentrations in the growing season (Figure 2). Wetland 1, the planted wetland, showed several periods of total phosphorus export from late September through November. As a result of these periods of export, total P decreased by only 27% in Wetland 1 compared to 40% in Wetland 2. In contrast, total phosphorus (TP) concentrations decreased by 48 and 47% respectively for Wetland 1 and Wetland 2 in 1998. The decreases through the basins were significant (α=0.05) but the two basins were not significantly different in phosphorus retention. TP decreased by 14% in Wetland 1 and 18% in Wetland 2 in 1997, but neither of these decreases was significant (α = 0.05).

Outflow concentrations were 92 and 76 µg-P/L in 1999, slightly lower than the 98 µg-P/L in both wetlands in 1998. The outflow was 125 µg-P/L in Wetland 1 and 120 µg-P/L in Wetland 2 in 1997 and 68 and 64 µg-P/L respectively in 1996.

In 1996, there was a clear pattern of decreasing concentrations of phosphorus from inflow to outflow but that pattern failed to develop in 1997. The pattern returned in 1998, with almost identical exponential decreases for both wetlands for total phosphorus. In 1999, the two wetlands appeared to diverge in spatial patterns of total phosphorus retention, with almost no phosphorus retention in Wetland 2 through the middle but some decrease in Wetland 1 (Figure 3).

Turbidity

Inflow turbidity averaged 25 NTU in 1999, the same as in 1998 while outflow measures were 19 and 20 NTU for Wetlands 1 and 2 respectively, higher than 1998's numbers (Table 2). Turbidity decreased by 24% in Wetland 1 and 18% in Wetland 2, less than the 36% in Wetland 1 and 37% in Wetland 2 seen in 1998.

Dissolved Oxygen

Dissolved oxygen continued to display significant diurnal patterns coupled to primary productivity and respiration but overall changes from inflow to outflow, taking into account dawn and dusk readings, were less. Overall, dissolved oxygen increased from 8.7 mg/L in the inflow to 9.1 mg/L in Wetland 1 outflow. But it decreased for almost the first time on an annual average in Wetland 2, although only to 8.6 mg/L. The increase in Wetland 1 was not significant; the decrease in Wetland 2 was. Dissolved oxygen averaged 12.0 and 11.7 mg/L respectively for Wetlands 1 and 2 outflows in 1998 and 11.4 and 11.3 mg/L respectively for Wetlands 1 and 2 outflows in 1997. These are early signs that oxygen demand is increasing in the sediments as organic carbon builds up.

Temperature

Temperature actually decreased through the wetlands by

Table 3. Water quality changes (+ indicates increase through wetland) and statistical significance at Olentangy River experimental wetlands, 1999. W1 = planted wetland; W2 = unplanted wetland; In = inflow; Out = outflow.

Parameter	% change W1 (+ = increase; - = decrease)	% change W2	Paired t-test, p-value In v. Out W1	In v. Out W2	Out W1 v. Out W2
Temp	-1.1	-2.1	nd	nd	0.0070
Turbidity	-24.3	-18.2	0.0001	0.0070	0.0044
D.O.	+4.9	-1.2	nd	0.0438	0.0001
pH	+ 1.7	+0.7	0.0001	0.0020	0.0001
Conductivity	-4.2	-3.1	0.0002	nd	0.0014
Redox	-6.3	-6.8	0.0001	0.0001	nd[1]
Total P	-27	-40	0.0128	0.0001	nd
SRP	-71	-75	0.0001	0.0001	nd
$NO_3 + NO_2$	-30	-33	0.0001	0.0001	nd

[1] nd = no significant difference at α = 0.05

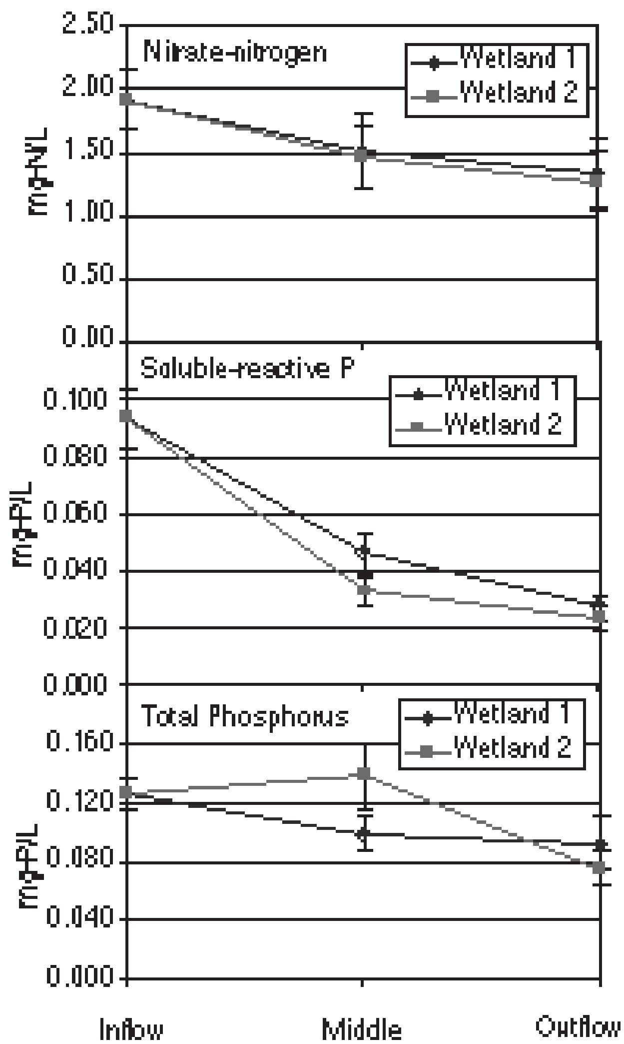

Figure 3. Decay of nitrate-nitrogen, soluble reactive phosphorus, and total phosphorus from inflow to outflow in experimental wetlands for 1999. Bars indicate standard error.

1 to 2 % although the changes were not significant. As recently as 1998 there was an annual average increase of 3.1% in Wetland 1 and 3.5% in Wetland 2; these differences were not statistically significant (α=0.05). But the outflow temperatures were significantly different (α=0.05). Wetland 2 outflow was cooler on average by 0.2°C.

Conductivity

Conductivity decreased by 3-4% through the wetlands, from an average of 550 µS/cm in the inflow to 527 and 533 in the outflows of Wetlands 1 and 2 respectively in 1999 (Table 2). The two wetlands were significantly different from one another in 1999. There were higher decreases of 10% in Wetland 1 and 7% in Wetland 2 in 1998 which were also significant (α=0.05). There was an average of 5 to 7% decrease in dissolved materials in 1997 and a 15% decrease in 1996. The decrease in dissolved ion concentrations from inflow to outflow, particularly in the growing season, is due to precipitation of calcium carbonate and other minerals caused by high pH that, in turn, is caused by the high water column productivity . But the decrease is becoming less as macrophytes grow and shade the water more each year.

pH

pH of the inflow waters from the Olentangy River averaged 7.74 in 1999, 8.18 in 1998, 7.94 in 1997, and 7.91 in 1996. Outflows of Wetlands 1 and 2 were significantly higher than the inflow (1.7 and 0.7% higher respectively) in 1999. Wetland 1 pH increase was significantly higher than that in Wetland 2 (α=0.05), the same situation as seen in 1998.

Redox

Redox potential continues to show little difference between the wetlands. Inflow averaged 302 mv while outflows of Wetlands 1 and 2 were 283 and 281 mv respectively (Table 2). The two wetlands did show significant decreases in redox from inflow to outflow (Table 3) and annual averages of outflow redox were the lowest of any year in this experiment.

Discussion

Differences between wetland basins in 6 years

Water quality data have now been collected at the Olentangy River Wetland experimental wetlands for six years. Of the 9 water quality parameters consistently measured over that period, there are now 5 that are significantly different between the two wetlands (Table 3). There were only 2 parameters that showed significant differences between the two wetland basin outflows in 1998, and 1 parameter in 1997 (Table 3). Mitsch et al. (1998) demonstrated that there were 4 different indicators in the first year (1994), followed by a divergence in water quality when 7 parameters were different in 1995, followed by convergence in 1996 when only 3 parameters were different. The sixth year results (1999) reported here suggest that there is a clear divergence again occurring due to *Typha* monoculture in Wetland 2 and a more diverse plant community in Wetland 1.

Changes over 6 years

Data have now been collected for six years on water quality changes through the two wetlands. Over the first three years, there was an average retention of 63% total phosphorus in both wetlands. The biggest differences between the two wetlands occurred in 1995 when Wetland 1 retained 8% more phosphorus than did Wetland 2. By the third year (1996), total phosphorus retention by the two basins was essentially the same and has remained so through 1998. Phosphorus retention in 1998 (27-40%) was approximately the same as the average of the two previous years (1997-98).

Soluble reactive phosphorus retention has been consistently high, with 71 to 75% retention in 1999, similar to the 63 to 67% retention in 1998 and the 61 to 66% retention in 1997. This remained the only parameter that has consistently shown greater than 50% retention in the wetland basins.

Nitrate-nitrogen retention has consistently been less than 50% and in fact, decreased from 47.5% retention in 1994 to 17.5% in 1997. The retention recovered to 33-39% in 1998 and 30-33% in 1999. There has been no dramatic difference in nitrate retention between the two wetlands over the 6 years.

Suspended materials, as measured by turbidity, decreased through the wetlands by 18 to 24% in 1999 and 36-37% in 1998, much better than the 4 to 6% retention rates in 1997. As expected, total phosphorus and suspended materials show similar patterns from year to year.

Dissolved material retention, as measured by conductivity reduction, was again greater in Wetland 1 than in Wetland 2 in 1999 although the percent decrease was less in 1999 than in previous years. Overall, dissolved materials decreased 3 to 4% in 1999, 7 to 9 % in 1998 and 5 to 7% in the wetlands in 1997. The significant decrease in conductivity was coupled with the more significant increase in pH in Wetland 1 compared to Wetland 2, probably due to higher algal productivity in Wetland 1 because of less macrophyte shading.

Since macrophyte community in the two wetlands began to diverge in diversity in 1998, water quality has followed suit. In 1995 when one wetland had considerably greater macrophyte cover than the other, we concluded that the effects of macrophytes on the water quality function of the wetlands was important (Mitsch et al. 1998). The basins have now diverged not only in macrophyte diversity and productivity but also in biogeochemistry.

References

American Public Health Association. 1989. Standard Methods for the Analysis of Wastewater, 17 ed., APHA, Washington, DC.

Harter, S.K. 1999. Patterns of short-term sedimentation in a freshwater created marsh. Master's Thesis, School of Natural Resources, The Ohio State University, 134 pp.

Kang, H. 1999. The significance of enzyme activities in wetland biogeochemistry. Ph.D. thesis, University of Wales, Bangor, UK.

Kang, H., C. Freeman, D. Lee and W.J. Mitsch. 1998. Enzyme activities in constructed wetlands: Implication for water quality amelioration. Hydrobiologia 368: 231-235.

Liptak, M. 2000. Primary productivity and phosphorus dynamics in experimental created marshes. Ph.D. disseration, Environmental Science Graduate Program, The Ohio State University, Columbus.

Mitsch, W.J., R.W. Nairn, X. Wu and A. Wehr. 1995. Water quality changes in Olentangy River water caused by the experimental wetlands at the Olentangy River Wetlands Research Park—first year results. In: Mitsch, W.J. and X. Wu (eds.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1994, Columbus, OH. pp. 51-61.

Mitsch, W.J. and R.W. Nairn. 1996. Nitrogen and phosphorus retention by the Olentangy River experimental wetlands, 1994-95. In: Mitsch, W.J.(ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 91-102.

Mitsch, W.J. and L. M. Carmichael. 1997. Water quality and nutrient removal patterns of created riparian wetlands: Third year results and a 3-year summary. In: Mitsch, W.J. (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 127-138.

Mitsch, W.J. and H. Montgomery, 1998. Water quality and nutrient removal patterns of created riparian wetlands: Fourth year results. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH, pp. 89-95.

Mitsch, W.J., X. Wu, R.W. Nairn, P.E. Weihe, N. Wang, R. Deal and C.E. Boucher. 1998. Creating and restoring wetlands: A whole-ecosystem experiment in self-design. BioScience 48: 1019-1030.

Mitsch, W.J., N. Wang, V. Bouchard, M. Ford and K. Mohler. 1999. Biochemical and nutrient removal patterns of created riparian wetlands: Sixth-year results. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1998. Columbus, OH, pp. 79-85.

Mortensen, P. and P. Lanzky. 1996. Water quality improvement in a constructed wetland, Thesis, Royal Danish School of Pharmacy, Copenhagen, Denmark.

Mortensen, P., P. Lanzky, and S.E. Jørgensen, 1997. Nitrogen removal by the Olentangy River experimental wetlands two years after construction. In: Mitsch, W.J.(ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 113-117.

Nairn, R.W. 1996. Biogeochemistry of newly created riparian wetlands: Evaluation of water quality changes and soil development. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Nairn, R.W. and W.J. Mitsch. 1997. Water quality changes in newly constructed riparian wetland, 1994-95. In: Mitsch, W.J., (ed.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1996, Columbus, OH. pp. 139-150.

Nairn, R.W. and W.J. Mitsch. 2000. Phosphorus removal in created wetland ponds receiving river overflow. Ecological Engineering 14: 107-126.

Spieles, D. J. 1998. Nutrient retention and macroinvertebrate community structure in constructed wetlands receiving wastewater and river water. Ph.D. dissertation, Environmental Science Graduate Program, The Ohio State University, Columbus, OH.

Spieles, D.J. and W.J. Mitsch, 1998. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997. Columbus, OH, pp. 105-117.

Spieles, D.J. and W.J. Mitsch. 2000. The effects of season and hydrologic and chemical loading on nitrate retention in constructed wetlands: A comparison of low and high nutrient riverine systems. Ecological Engineering 14: 77-91.

U.S. Environmental Protection Agency. 1979. Methods for chemical analysis of water and wastes. 600/4-79-020, U.S. Environmental Protection Agency, Cincinnati, OH.

U.S. Environmental Protection Agency. 1983. Methods for chemical analysis of water and wastes. 600/4-79-020, U.S. Environmental Protection Agency, Cincinnati, OH.

Vorwerk, N. 1997. Comparison of three years of pH values between planted and unplanted wetlands. Honors thesis, School of Natural Resources, The Ohio State University.

Vorwerk, N. and W.J. Mitsch. 1998. Comparison of three years of pH values between planted and unplanted wetlands. In: Mitsch, W.J. and V. Bouchard (eds.), Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1997, Columbus, OH. pp. 97-104.

Wehr, A. 1995. Early water quality of created wetlands at the Olentangy River Wetland Research Park. Honors thesis, School of Natural Resources, The Ohio State University.

Wehr, A. and W.J. Mitsch. 1996. Early water quality of created wetlands at the Olentangy River Wetland Research Park. In: Mitsch, W.J.(ed.) Olentangy River Wetland Research Park at The Ohio State University, Annual Report 1995, Columbus, OH. pp. 83-90.

YSI Incorporated, 1996. 6000UPG Multi-parameter Water Quality Monitor—Instruction Manual. YSI Incorporated, Yellow Springs, OH.